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TEMPORAL ACUITY OF THE VISUAL SYSTEM

by

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ABSTRACT

In the present study, the effects of three variables (pulse-to-cycle fraction, intensity of the light source, and target size) upon critical flicker frequency were investigated.

The primary purpose of the study was to investigate a controversial prediction by Bartley and Nelson (1960a, 1960b, and 1961) following from a model which was based upon discharge characteristics of the optic nerve. The prediction was that flicker would always be obtained when extremely small PCF's were employed. There would therefore be a flicker-fusion transition at low PCF's and higher CFF's should be obtained as PCF's become smaller.

The results are contrary to that prediction. A discussion arguing that the prediction does not properly follow from the neurophysiological model is presented.

An elaboration of Geldard's (1953) analogy between spatial and temporal acuity is presented. It is argued that CFF constitutes a sensitivity measure which is the temporal analogue of spatial acuity sensitivity measures.

The data are interpreted in light of Nelson and Bartley's (1965) theory. The two primary factors of that theory are 1) optical channels which extend from the eye to the brain and 2) the "density" of discharge activity manifested in the visual cortex.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

"When a series of equally spaced flashes of light strikes the retina, flicker is likely to result. Whether flicker will be seen and what its appearance will be are primarily determined by the flash frequency. When it is low the contrast between darkness and the flash is great. As frequency is increased there is a reduction in contrast, and at a sufficiently high rate of repetition the individual flashes will not be sensed at all. The point at which flicker just disappears is known as the critical fusion frequency" (Geldard, 1953, P.87). Geldard argued further that "in the critical fusion point we have a measure of visual temporal acuity, analogous to visual spatial acuity measures..." (1953, P.89)

Many theories have been formulated to explain this ability of the visual system to resolve temporal separation of pulses when a train of intermittent photic stimuli is presented to the eye. The bases of these theories range from a focus on the photochemical changes in the rods and cones to a primary concern with cortical response patterns. Nelson and Bartley (1965) provided a theory for CFF that involved neural activity in "parallel channels extending from the eye to the brain" (1965, P.187). According to that theory, if the cortical activity in these channels is relatively synchronous, flicker will be the resultant perception. If, on the other hand, the cortical activity

is asynchronous and the density of neural discharge per unit of time is uniform, fusion rather than flicker will be perceived.

The primary focus of concern for this investigation is an earlier, though related, neurophsiological model proposed by Bartley and Nelson (1960a, 1960b, and 1961). The model itself is based upon discharge characteristics of the optic nerves of cats and rabbits as reported by Bartley and Bishop (1940 and 1942) and Granit and Therman (1935).

Bartley describes the optic nerve discharge in terms of "on" and "off" responses. The "on" responses of the optic nerve consists of a burst of neural discharge that appears 15 to 25 msec. after the presentation of a pulse of light to the eye. This discharge lasts for the duration of the stimulus presentation and stops virtually upon termination of that presentation. The amplitude of the summed discharges for this type of response is primarily determined by the intensity of the stimulus. As stimulus intensity decreases, the amplitude of the response shows a corresponding decrease. Very low stimulus intensities fail to evoke the "on" response.

The "off" response is comprised of a burst of neural activity that characteristically appears 15 to 60 msec. after the termination of the stimulus presentation. The amplitude of this response is primarily determined by the

duration of the pulse presentation that precedes it. The amplitude of this type of discharge decreases as the length of the presentation is reduced. Stimulus presentations shorter than seven msec. fail to evoke an "off" response regardless of the stimulus intensity (Bartley and Bishop, 1940).

Thus, one of the primary differences between the "on" and "off" discharges is that "on" responses will be evoked by short pulses of light that fail to evoke "off" responses. If the pulse length were increased, the "off" response would begin to appear.

Research by Granit and Therman (1935) on the retinal response to photic stimulation established that when a second pulse of light is presented soon after the termination of the first pulse, the "on" response to the second pulse inhibits the "off" response to the first pulse. Thus, if two successive pulses of light were presented to the eye, and if the temporal separation between the two pulses were very short, the "off" response to the first pulse would be inhibited by the "on" response evoked by the second.

Bartley and Nelson (1960a, 1960b, 1961) incorporated these findings into a model from which rather unique predictions were made. These predictions concerned the influence pulse-to-cycle fraction (PCF) has upon critical flicker frequency (CFF). If the intensity of the stimulus

and the rate of stimulus presentation were kept constant in a combination such that CFF is nearly attained with the smallest PCF, the following changes in CFF would be expected to occur as PCF were varied from one extreme (very small) to another (very large).

The smallest PCF would fail to elicit "off" responses since the duration of the pulses would be too short. The "on" responses would be of short duration and the "null period" (interval between pulses) would be relatively long. There would be equally long intervals between the "on" responses which would give rise to the perception of flicker. As the theory was originally stated, flicker would always be predicted when very small PCF's were used. There has been some controversy about this latter point; this matter will be considered later in more detail.

As PCF is increased, the pulse of light would constitute more of the cycle time. The "on" responses would, therefore, also last proportionally longer. The "null periods" would be smaller and the time between "on" responses would be decreased significantly. Since the pulse length would still be too short to evoke "off" responses, and since the temporal separation between the "on" responses would be too short to produce flicker, the light would appear fused.

Further increase of PCF would lengthen pulse duration sufficiently to evoke "off" response. "... the off-

response would constitute a specific signal for cessation of pulses throughout a certain duration range, and thus introduce flicker when shorter pulses failed to do this since they do not elicit off-responses" (Bartley and Nelson, 1960b, P.241). This prediction is unique to this model and is contrary to the expectations of other theories. Once the combination of PCF, rate of presentation, and stimulus intensity were found that just eliminated flicker; traditional theories would predict that a further increase of PCF would increase the brightness of the target (Talbot-Plateau Law) but would not reintroduce flicker.

As a very large PCF is introduced, the "null period" would be short enough that the "on" response to the latter pulse would inhibit the "off" response to the preceding pulse. As the "off" responses were inhibited, fusion would again be introduced.

Thus, as PCF is varied from the small extremes to the largest, there are three flicker-fusion transitions. As PCF increases, the perception of flicker changes to the perception of fusion, then fusion to flicker, and lastly flicker to fusion.

Investigations by Bartley and Nelson (1960a, 1960b, 1961) confirmed the second and third flicker-fusion transitions. As PCF was increased so that the "off" response would be evoked, the perception of fusion yielded to that of flicker. As PCF was further increased, flicker changed

to fusion, as was to be expected with inhibition of the "off" response.

The prediction that flicker would always be obtained when extremely low PCF's were employed was not confirmed. Except when the higher intensities were used, fusion rather than flicker resulted from the lowest PCF. Thus, the first expected flicker-to-fusion transition was obtained only when higher stimulus intensities were used. These results brought Bartley and Nelson to "reconstruct the theory by elimination of this particular supposition. As one shortens pulses... brightness would be expected to become so low that the whole process of seeing flicker would become impossible and so a steady field would be the result until intensive threshold itself is approached, in which case very long reversals between seeing something and nothing would supervene" (1961, P.45).

Throsby did not condone this latter revision of the theory and maintained that flicker had to be obtained with the low PCF's before the theory could be confirmed. Data by Lloyd and Landis (1960) which suggested the appearance of flicker at extremely low PCF's was dismissed as exhibiting random variation and was considered to be due "almost certainly (to) experimental error" (Throsby, 1962, P.514).

In a reply to Throsby, Bartley explained the failure to find the first flicker-to-fusion transition: "our

apparatus did not provide for the full extension of conditions to determine empirically that a third transition between flicker and fusion would occur" (Bartley, 1964, P.71).

PURPOSE

The primary purpose of this study was to investigate whether or not this transition exists.

The apparatus used allowed PCF to be varied to the extremely small (and extremely large) values necessary for the investigation. Thus, PCF values smaller than those employed by Bartley and Nelson (1960a, 1960b, and 1961) were readily attained. The wider range of PCF values also give a more comprehensive picture of the influence of that variable on CFF.

Bartley and Nelson (1960a, 1960b, and 1961), as well as Lloyd and Landis (1960), employed targets, the largest of which covered an area of two degrees. In this study, larger targets were also employed. It was expected that the increase in retinal illuminance created by the increase in target size would reduce the loss of total flux usually incurred as PCF is decreased. The resultant increase in retinal illuminance was intended to make the flickering target visible at extremely low PCF values.

Another purpose of the study was to explore and elaborate upon Geldard's analogy between <u>spatial</u> and <u>temporal</u> acuity. The intention was to investigate whether or not variables known to produce a given effect upon spatial acuity will produce an analogous effect upon temporal acuity. In effect, the question concerns how analogous temporal acuity is to spatial acuity.

If the analogy is a good one, we can use CFF as a measure of the efficiency of the visual system. Just as we use measures of _spatial_ acuity to determine how efficient the visual system is in resolving spatial separation between stimuli; CFF, as a measure of _temporal_ acuity, can be used to determine the efficiency of the visual system in resolving temporal separation between stimuli.

APPARATUS

The apparatus was designed to generate pulse-forms that were "square" rather than sinusoidal. This requirement for "square" pulses becomes more difficult to meet as PCF is reduced to extremely small ratios.

Since the temporal intermittency of the stimulation had to be controlled solely by the episcotister, the confounding intermittency that would have been induced by an a-c power supply had to be precluded.

Another requirement concerned the luminance of the light source. As PCF is reduced to extremely low ratios, the brightness of the target can be reduced to the level that the target can barely be seen, if it can be seen at all. Since one of the primary purposes of the study was to investigate the effect of very small PCF's on CFF, the luminance of the light source had to be sufficient for the target to be seen when the smallest PCF's and target sizes were employed.

Light Source

The photic source employed was a xenon arc lamp (Mazda, 250w) which received current from a d-c power supply. For further descriptions of the xenon arc lamp, see Boynton (1966) and Wyszecki and Stiles (1967).

There were two advantages of this source for the present study. First, the extremely high output in the visible regions achieved by the lamp allows for investigation

of differences in CFF employing very small PCF's. This is not possible with sources of low intensity.[1] Second, it was desired that stimulus intermittency be controlled solely by an episcotister. The xenon arc source is driven by a continuous current and does not produce any regular or irregular undulations to confound experimental control of the rate of repetition.[2]

Optical System

Stimulation was delivered to the eye by a single-channel Maxwellian-view optical system (Riggs, 1965; and Boynton, 1966). Starting at the source and progressing to the eye, the instrumental sequence was as follows: The system began with the xenon arc lamp which was followed by a lens which collimated the light, a field stop with a one inch aperture, a lens bringing the image to a focus, another lens to collimate the light, a Bell and Howell micro-fit tray to accommodate neutral density filters, an iris diaphram (Edmund Scientific Co., Stock No. 30118) used to control the size of the target, a lens to focus the image within the pupil of the eye, and an artificial pupil.

With the exception of the lamp, the last lens, and the artificial pupil, all of the components of the optical system were attached by hinged carriages to a Cenco lathe type optical bench (Central Scientific Company, PG 3055, No. 85801). The optical bench itself was bolted to a

sturdy wooden box frame constructed of 3/4 inch plywood The box, which was employed to raise the optical bench to the appropriate level, was fastened securely to a five foot table and to the observer's booth by angle braces. Angle braces were also employed to rigidly attach the table to the observer's booth. All this served to rigidly control the alignment of stimulation to the O.

The last lens referred to was cylindrical and was mounted in a hole which was cut into the observer's booth. The artificial pupil referred to was a 2 mm aperture drilled into a copper disk. This was itself mounted in an open end of a brass tube (1 inch diameter). The two and one half inch long tube was in turn mounted on a 6 1/2 inch X 5 inch brass plate, and the plate fastened to a frame constructed from aluminum rods (1/2 inch diameter) and Fisher "flexaframe" right-angle connectors. The frame was firmly attached to the inside wall of the observer's booth and served to help rigidly align the stimulating device to the O.

The artificial pupil also served as a sighting device and aided the subject in properly adjusting both the bite bar and head-rest before each session. The bite bar and head-rest were both easily adjusted on the rod frame described above.

The observer's booth was well ventilated and was effectively a dark room.

Episcotister

The blade of the episcotister was machined out of a 1/8 inch thickness of aluminum and was 32 inches in diameter. An aluminum band (2 1/2 inches wide and 32 inches at its outermost diameter) was designed to fasten to the rim of the episcotister. The band was cut into quarters and each quarter of the band was secured to the rim of the episcotister by four 1/4 inch bolts. PCF was varied by loosening the bolts and inserting vanes between the band and the rim of the wheel.

The advantage of a large episcotister blade is that it removes various practical restrictions limiting the range of PCF's. Very small PCF's cannot adequately be investigated when the blade is small in diameter since the size of the opening in the sectored disk soon becomes too narrow to fully expose the entire target as PCF is decreased. Also, at PCF's where the opening in the blade just matches the visual angle of the target, sinuoidal shaped pulse-forms are produced. The large episcotister used in this study was designed so that the open sectors would be relatively large even when extremely small PCF's were employed. Thus, markedly sinusoidal pulse forms should have been avoided even at the smallest PCF. The pulse-forms actually obtained are represented in Appendix A.

The episcotister blade was driven by a heavy series wound motor secured to a heavy iron stand. Rotation speed

was controlled by a variable auto-transformer (Adjust-a-volt, type 500B). This combination of motor and control allowed for rapid changes in speed and braking. Lighter units are difficult to control since the inertia of a large episcotister blade causes the accelerating or decelerating blade to "slide" out of the range of speeds desired. Cycles per second were detected by a photocell and were read from a d-c microamperes meter.

The episcotister was mounted to chop the photic beam at that point at which the image was first brought to a focus. This further reduced the sinusoidal character of the output.

The rest of the optical system was covered with black light-proof material to reduce stray illumination in the room.

<u>Pulse Forms</u>

Because of the requirement that the pulse-forms remain "square" rather than becoming sinusoidal as PCF is decreased, Appendix A should be examined carefully. Despite the attempt to design an apparatus that would generate pulse-forms that were "square" rather than sinusoidal, it should be noted that the rise and fall times constitute a relatively large proportion of the pulse duration for the smallest PCF.

Unfortunately, the apparatus was not successful in obviating the same problems that have frustrated other

investigators (Lloyd and Landis, 1960) as PCF was varied to extreme values.

METHOD

Stimulus Specifications

Stimulus intensity was controlled by Tiffen neutral density filters. The intensities of the two luminance levels employed were 1674 ft-candles and 67 ft-candles.[3]

Target size was manipulated by means of an iris diaphram. The visual angles of the four different target sizes were 1°, 2°, 5°, and 10°.

Eight PCF's were used: 1/128, 1/64, 1/32, 1/8, 1/4, 1/2, 3/4, and 7/8.

Observers

Both Os were male students in the Department of Psychology who were experienced at making CFF judgments. T.N. was a graduate student and B.M. was an undergraduate student. Any of the observers' visual defects were adequately corrected.

Procedure

Each experimental session lasted for about one hour and began by having O dark-adapt for five minutes in the observer's booth.

Alternating ascending (flicker-to-fusion) and descending (fusion-to-flicker) methods of varying rate were employed with E controlling the rate of change. Observers reported CFF by pushing the button on a cordswitch. On ascending trials, Os were instructed to report CFF when the target appeared to be steady and all signs of undulation within

the target itself had disappeared. For descending trials, the criterion for CFF was the first appearance of flicker or ripple in any part of the target.

Because an _O_ would light-adapt to a brighter target faster than he would dark-adapt to a dimmer one, an attempt was made to order the presentation of the stimulus conditions so that the brighter target conditions would follow those conditions that were less bright (i.e., the lowest stimulus intensity before the highest intensity, the smaller targets before the larger targets, and the smaller PCF's before the larger PCF's). As a result, all judgments to have been made at the lowest stimulus intensity were recorded before the highest intensity was employed.

Since PCF was the most important of the independent variables in the study, it would have been ideal to progress from the smallest PCF to the largest before changing either of the other independent variables. But the time and difficulty involved in changing PCF made such an operation impractical. Too much time would have been required to change the PCF eight times. Therefore, it would not have been possible to employ all eight PCF's in one experimental session. In a subsequent session, it would have been necessary to follow the presentation of the largest PCF (7/8) by the presentation of the smallest (1/128). In effect, this change in PCF would have produced a significant decrease in the intensity (compensated to

Talbot-level) for which O would not have been dark-adapted.

Also, the actual mechanical task of changing vanes to produce large differences in PCF would have been unwieldy and was likely to result in a mistake in the experimental procedure.

To avoid the difficulties described above, an alternative method of sequentially ordering PCF was adopted. During the first session employing a given stimulus intensity, the three smallest PCF's (1/128, 1/64, and 1/32) were used. Beginning with the 1° target and the PCF of 1/128, all responses were recorded for that set of stimulus conditions. Then, maintaining the same target size and light intensity, all responses were recorded for the PCF of 1/64 followed by the PCF of 1/32.

Target size was then increased in size to subtend a visual angle of 2° and PCF was again progressively increased from 1/128 to 1/32.

During the second session, the same general procedure was employed using target sizes that subtend visual angles of 5° and 10° respectively.

Two PCF's (1/8 and 1/4) were employed during the third session. Since there were only two PCF's used, it was possible to present each PCF with each target size during one session.

The fourth and fifth experimental sessions were similar to sessions one and two. The only difference in

these last two sessions was that they employed PCF's of 1/2, 3/4, and 7/8 instead of PCF's 1/128, 1/64, and 1/32 respectively.

Upon presentation of a new set of stimulus conditions, O was required to make "practice" judgments until he became light-adapted to the new conditions. The O was judged to be light-adapted when his judgments appeared to become reliable.

RESULTS

The data are represented as means in Table 1. Each mean is based upon eight observations.

Generally, the data shows that CFF increases with intensity, increases with target size, and shows a curvilinear relationship with PCF. The curvilinear relationship between CFF and PCF is illustrated in Figures 1 and 2.

The summary of the analysis of variance is presented in Table 2. The overall difference between observers was not significant ($F<1$, 1 and 14 d.f.). As shown in Figure 1, the data plots for both Os were nearly identical. The only difference between the plots rests upon the fact that BM generally reported CFF at consistently, though not significantly, higher values than did TN. This is probably due to the Os using slightly different criteria while judging CFF.

The difference between intensities failed to reach significance ($F = 1.43$, 1 and 14 d.f., $p>0.05$). However, as shown in Figure 2, there is a clear-cut increase in CFF as intensity increases. The failure of this main effect to attain significance by analysis of variance is attributable to the fact that only two intensities were employed. This severely restricted the degrees of freedom and therefore required a much larger F ratio for significance.

The PCF main effect was significant ($F = 12.25$, 7

and 98 d.f., $p<.01$) as was the main effect attributable to target size ($F = 170.77$, 3 and 42 d.f., $p<.01$). As shown in Table 3, an increase in target size produces an increase in CFF. This finding is consistent with the Granit-Harper Law.

The observers x target size interaction ($F = 16.18$, 3 and 42 d.f., $p<.01$) was significant. Table 3 indicates that as the visual angle of the target increases from 1° to 2°, CFF for both TN and BM increases at the same rate with TN reaching CFF at slightly higher values than BM. As the target size increases to 5° and 10° of visual angle, the rate of increase in CFF decreases somewhat for TN but increases significantly for BM. For the 5° and 10° targets, BM has noticeably higher CFF values than does TN.

The observers x PCF x target size interaction was significant ($F = 1.89$, 21 and 294 d.f., $p<.05$) but failed to reach significance when tested by the Greenhouse and Geisser (1958) conservative method ($F = 1.89$, 1 and 14 d.f., $p>.05$). In any case, this interaction is not of any importance. It would be concerned with how the observers x target size interaction, as described above, varied in some manner with PCF.

None of the other interactions were found to be significant.

In order to further investigate the effects of intensity upon CFF (Ferry-Porter Law), the subjective intensity[4]

(Talbot-level was calculated for each PCF-stimulus intensity condition (see Table 4). The logarithms of the subjective intensities compensated to Talbot-level and their corresponding CFF values are presented in Tables 5 and 6.

Table 7 summarizes the linear correlation of CFF and the logarithms of the subjective stimulus intensity. As is indicated, the slopes (regression coefficients) of the regression lines are virtually identical.

The increase in the _y_-intercept accompanying the increase in target size is consistent with the Granit-Harper Law as well as the Target Size main effect reported in the Analysis of Variance.

All of the correlation coefficients were highly significant ($t>9.0$, 14 d.f., $p<.01$) and are entirely consistent with the prediction following from the Ferry-Porter Law.

The linear regression plot for the combined data cited in Table 7 is shown in Figure 3.

Perusal of Figure 3 indicates that there are four data points which fall noticeably lower (relative to the regression line) than do the other data points. As shown in Table 4, PCF of 3/4 obtains log values of 1.701 and 3.099 for low and high stimulus intensity respectively. The corresponding log values for PCF of 7/8 are 1.768 and 3.166. It is clear that the outstanding data points

in Figure 3 represent the mean CFF values for the largest PCF's at both the high and low stimulus intensities.

The data in Table 6 shows a corresponding decrease in CFF for PCF's of 3/4 and 7/8. With one exception, this decrease is shown across all target sizes for both Os.

If lines were drawn through the data points corresponding to PCF's of 3/4 and 7/8 in Figure 3, the lines would be parallel to the regression line. These results are generally consistent with the findings of Ross (1938) and would seem to require an addendum to the Ferry- Porter Law. This addendum would describe a family of curves, one for each of the larger PCF's.

This decrease in CFF at PCF's of 3/4 and 7/8 can readily be interpreted in terms of the "off" response. Clearly, as predicted from Bartley's model, as PCF becomes large, the null period becomes so short that the "off" response of the preceding pulse is inhibited by the "on" response of the succeeding pulse.

To further investigate Bartley's prediction that CFF would obtain higher values at extremely small PCF's, CFF was plotted against the duration of the pulse interval (Figure 4). Given that Bartley's prediction is correct, CFF should increase rapidly as the duration of the pulse-time becomes extremely short. The data shown in Figure 4 indicate the opposite to occur. As pulse-time decreases from approximately 10 msec., there is a rapid decrease in

CFF. Since Bartley further restricted his prediction to higher intersities, the data shown in Figure 4 are plotted for both low and high intensities. As is illustrated, the plots for the two intensities are nearly identical in shape with the higher intensity curve raised above the low intensity curve.

Generally, the most efficient pulse-time (i.e., the light interval producing the highest CFF) appears to be between 10 and 15 msec. in length.

CFF is plotted against the duration of the "dark" interval in Figure 5. The most efficient null period ("dark" interval) is 10 to 13 msec. long.

DISCUSSION

The Granit-Harper Law is a descriptive formulation relating CFF to target size. Briefly, the Granit-Harper Law states that CFF increases linearly with the logarithm of the stimulus area.

The results confirm the prediction of the Granit-Harper Law and are consistent with findings cited by Brown (1966, P.253). The significant difference in CFF due to target size is reflected by the means in Table 3. These means illustrate the increase in CFF accompanying the increasing target size.

This is further illustrated in Table 7. As CFF was plotted linearly across the logarithm of the compensated intensity, the slopes of the regression lines in each of the plots are virtually identical. The only noticeable difference concerns the intercepts. As the target size increases from visual angles of 1° through 10°, the intercepts show a corresponding increase. These results are comparable to those of Hecht and Smith (1936) and Granit and Harper (1930).

The results cited in Table 7 and partially illustrated in Figure 3 also conform to the prediction of the Ferry-Porter Law. This las predicts that CFF will increase linearly with the logaritm of the luminance. The highly significant linear correlations between CFF and the logarithm of the luminance values are precisely what would

be predicted by the Ferry-Porter formulation. These results compare nicely with those of Granit and Harper (1930).

As proposed in the introduction, one of the purposes of this research was to evaluate and elaborate upon Geldard's analogy between temporal and spatial acuity of the visual system. One method of assessing the validity of the analogy is to determine if certain variables have similar effects upon both spatial and temporal acuity measures. As the correspondence improves, the analogy becomes better.

One method of investigating spatial acuity (Riggs, 1966) involves presenting a grating consisting of alternating light and dark stripes. The separation between light or dark stripes in the grating can be varied by increasing or decreasing the width of those stripes. Generally, as the width of the stripes is increased, the individual stripes become more prominent and the separation between the stripes becomes more apparent. As the width of the stripes decreases, the stripes themselves become less prominent as the separation between them becomes less apparent. Finally, the width of the stripes is decreased to a point that the spatial separation between the stripes can just barely be detected. If the width of the stripes is decreased further, the grating loses its striped appearance and looks evenly gray. The visual angle of the stripe width which can just barely be resolved is usually

measured in terms of minutes. The reciprocal of this visual angle in minutes is the sensitivity measure which is used to define spatial acuity.

The close resemblance between this spatial sensitivity measure and CFF seems apparent. In flicker-fusion research, a train of intermittent photic pulses is presented to the visual system. At low rates of presentation, the pulse-times and dark-times are long enough that the individual pulses can be resolved. By increasing The rate of presentation, the cycle-time (pulse-time plus dark-time) can be shortened to the extent that no temporal separation between the pulses can be resolved. At this rate, the light appears to be fused with no temporal variation in brightness. The reciprocal of this cycle-time in seconds is expressed as CFF.

Thus, CFF as a sensitivity measure for temporal acuity is clearly analogous to the sensitivity measure for spatial acuity.

Cornsweet (1970) and Kelly (1961) use Fourier analysis to predict both spatial and temporal acuity. To apply this model, the visual stimulation is analyzed into its Fourier components (sine waves). The components are then evaluated according to the appropriate modulation transfer function (MTF). The attenuated components are then combined (Fourier synthesis) to predict the resultant perception. The prediction of spatial and temporal acuity generated by this model are extremely accurate. The fact

that the same model can be used to predict both spatial and temporal acuity suggests that the visual system handles frequency stimulation, both temporal and spatial, in an analogous manner.

Spatial acuity is usually depicted as increasing linearly with the logarithm of retinal illuminance (Riggs, 1966, P. 336-337). As predicted by the Ferry-Porter Law, and as illustrated by the data (Figure 3), an analogous relationship is obtained between temporal acuity and total flux.

As mentioned in the introduction, one of the primary purposes of the study was to investigate a prediction following from the neurophysiological model proposed by Bartley and Nelson. The prediction was that, providing the stimulus intensity was sufficient, flicker would always be obtained as PCF is made very small and pulses of very short duration are presented.

The results of this study are clearly contrary to this prediction. The data plotted in Figures 1 and 2 show no suggestion of higher CFF values at lower PCF's.

The interpretation of the results are the same when they are plotted differently in Figure 4. As pulse duration is decreased from approximately 10 msec., there is a decrease in CFF. Significantly, as pulse duration is reduced, the <u>rate</u> of decrease in CFF becomes <u>greater</u>. It is important to note that in Figures 2 and 4, the results

are obtained for both high and low stimulus intensities.

To summarize the implications of these data for Bartley's early model, the fusion-to-flicker transition predicted for extremely small PCF's was not confirmed. However, it seems that this prediction did not properly follow from the model in any case. The model is formally a neurophysiological one which is based upon "on" and "off" responses of the optic nerve. The predicted flicker-fusion transitions that are formally based upon the neurophysiological model (i.e., are based upon the "on" and "off" discharges of the optic nerve) have been reconfirmed repeatedly (Bartley and Nelson, 1960a, 1960b, and 1961). Since the predicted flicker-fusion transition at extremely small PCF's does not properly follow from the neurophysiological model, the model cannot be faulted when that prediction is not confirmed.

Nelson and Bartley's later theory (1965) more adequately accounts for the results of this investigation. As mentioned in the introduction, this theory involves two factors: optical channels extending from the eye to the brain and the "density" of neural activity at the visual cortex.

The optical channels are defined as "individual optic-nerve fibers. Central portions of the channels are complex interlaced circuits and function temporally in ways controlling activities that feed into them. These circuits are neurophysiological entities governed by well-known properties

such as inhibition, facilitation, etc." (Nelson and Bartley, 1965, P.187).

Density is described as a "time-dependent variable in pathway activity". It "refers to the discharge activity per unit time and is defined as the reciprocal of separations between channel discharges. Flicker and fusion have been associated with uniformity of discharge density or a uniform gradient of discharge density over some unit of time. According to the theory, flicker is maintained only so long as critical values of irregularity of density persist" (Nelson and Bartley, 1965, P.188).

Using this model as an interpretive device, the data obtained in the present study can readily be explained.

When the extremely small PCF's are employed, few of the channels will discharge and the distribution of the discharge density will be too uniform to produce the perception of flicker. As the PCF is increased, there will be a corresponding increase in pulse duration. Until the pulse duration reaches the "critical period", this increase in pulse duration will manifest a temporal summation sufficient to activate those channels with higher thresholds. After the "critical period" is reached, the general effect of increasing pulse duration would be to spread the discharge density more uniformly across the distribution. When PCF is increased still further, the pulse duration will become sufficient to evoke an "off"

discharge. This will increase synchronous activity within the system and will have the effect of decreasing the uniformity of the discharge density. A further increase in PCF would decrease the dark-time or null period to the extent that the "off" response would be inhibited (as described earlier). The elimination of the "off" response would significantly increase the uniformity of density gradient, as would further increase in PCF.

The theory also adequately explains the effects of increased intensity upon CFF. "Intensity is effective in increasing CFF in so far as it puts more channels into activation; hence increases the likelihood of residual synchrony being maintained at higher rates of repetition" (Nelson and Bartley, 1965, P.191).

A similar explanation describes the relationship between CFF and target size. Not only would the larger target size activate more channels by manifesting temporal summation, but it would bring a different population of visual channels into play (i.e., it would activate scotopic as well as photopic units).

FOOTNOTES

[1] The Talbot-Plateau Law states that the brightness of the target at fusion decreases proportionally to the decrease in PCF. A stimulus source of low intensity is increasingly more difficult to see as PCF is decreased.

[2] If alternation current had been used, a 60 cps "ripple" would have been obtained and superimposed upon the intermittent stimulation presented to the eye.

[3] Since reliable measures of luminance cannot be taken directly from a Maxwellian view, it was necessary to first match a comparison stimulus for brightness with the target as seen through the Maxwellian view. The intensity of the comparison stimulus was then measured with a MacBeth Illuminometer (Leeds & Northrup, No. 6800).

[4] The Ferry-Porter formulation is commonly expressed as follows:

$$F = k \times \log I + c$$

There exists some controversy among authorities regarding the "I" in the equation. Some feel that "I" stands for the luminance of the light source. Others, such as Le Grande (1968), argue that "I" stands for "the effective intensity of a rhythmically interrupted stimulus as given by the Talbot-Plateau law" (Rubin and Walls, 1969, P. 307). The latter interpretation has been adopted by this writer.

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TABLES

Table 1: Mean CFF Reported as Cycles per Second

Observers:		TN		BM	
PCF	Target Size	Low Intensity	High Intensity	Low Intensity	High Intensity
1/128	1°	15.1	31.4	16.6	25.6
	2°	16.0	34.8	17.2	30.9
	5°	16.9	35.5	18.5	37.8
	10°	18.5	36.1	22.1	40.1
1/64	1°	15.9	32.1	15.9	30.9
	2°	17.6	37.8	17.9	32.2
	5°	18.5	38.2	21.0	40.0
	10°	21.4	39.4	26.9	42.2
1/32	1°	19.4	36.8	17.5	32.5
	2°	19.1	36.8	20.2	36.6
	5°	22.5	40.9	25.6	42.5
	10°	25.1	41.2	28.8	44.1
1/8	1°	27.8	37.8	25.2	40.2
	2°	28.6	42.1	28.5	44.8
	5°	31.8	45.0	31.2	48.4
	10°	35.4	45.1	33.8	50.9
1/4	1°	30.1	40.1	27.8	44.2
	2°	31.6	44.2	28.9	47.4
	5°	37.6	46.4	33.2	50.0
	10°	38.2	46.0	38.2	53.9
1/2	1°	31.2	44.0	30.2	42.0
	2°	34.2	46.1	33.8	47.5
	5°	34.4	45.6	36.5	52.0
	10°	37.0	46.0	42.6	51.6
3/4	1°	26.4	41.0	26.2	39.8
	2°	30.1	43.5	29.4	42.8
	5°	31.6	43.2	37.0	46.8
	10°	34.8	46.5	39.6	48.4
7/8	1°	22.9	37.0	20.6	35.1
	2°	25.0	38.5	25.1	38.4
	5°	27.6	40.0	31.4	42.0
	10°	30.5	42.2	33.8	44.5

Table 2: Analysis of Variance

Source	Sum of Squares	d.f.	Mean Square	F	p
Observers	334.2	1	334.2	0.06	
Error	77547.8	14	5539.1		
Intensity	463.6	1	463.6	1.43	
Obs x Inty	3.6	1	3.6	0.01	
Error	4552.3	14	325.2		
PCF	122.2	7	17.5	12.25	.01
Obs x PCF	10.9	7	1.6	1.09	
Error	139.7	98	1.4		
Inty x PCF	11.2	7	1.6	1.74	
Obs x Inty x PCF	6.0	7	0.8	0.93	
Error	90.0	98	0.9		
Target Size	10130.4	3	3376.8	170.77	.01
Obs x Size	959.9	3	320.0	16.18	.01
Error	830.5	42	19.8		
Inty x Size	18.9	3	6.3	0.64	
Obs x Inty x Size	2.6	3	0.9	0.09	
Error	414.4	42	9.9		
PCF x Size	21.8	21	1.0	1.12	
Obs x PCF x Size	36.8	21	1.8	1.89	.05
Error	272.4	294	0.9		
Inty x PCF x Size	24.0	21	1.1	1.42	
Obs x Inty x PCF x Size	19.0	21	0.9	1.12	
Error	237.9	294	0.8		
Total	96250.1	1023			

Table 3: Mean CFF as a Function of Target Size

Visual Angle of Target	Observer		Combined
	TN	BM	
1°	30.6	29.4	30.0
2°	32.9	32.6	32.7
5°	34.7	37.1	35.9
10°	36.5	40.1	38.3

Table 4: Compensation of Stimulus Intensities for Talbot-level and Logs of the Compensated Values

Intensity	PCF	Subjective Intensity in Ft-Candles	Log Compensated Value
66.976 ft-candles	1/128	0.523	-0.281
	1/64	1.046	0.020
	1/32	2.093	0.321
	1/8	8.372	0.923
	1/4	16.744	1.224
	1/2	33.488	1.525
	3/4	50.232	1.701
	7/8	58.604	1.768
1674.40 ft-candles	1/128	13.081	1.117
	1/64	26.162	1.418
	1/32	52.325	1.719
	1/8	209.300	2.321
	1/4	418.600	2.622
	1/2	837.200	2.923
	3/4	1255.800	3.099
	7/8	1465.100	3.166

Table 5: Mean CFF as a Function of the Log of Stimulus Intensities Compensated to Talbot-level

Intensity	Log of Compensated Intensity in ft-candles	TN Mean CFF	BM Mean CFF	Combined Mean CFF
Low	-0.281	16.6	18.6	17.6
	0.020	18.3	20.4	19.4
	0.321	21.5	23.0	22.3
	0.923	30.9	29.7	30.3
	1.224	34.4	32.0	33.2
	1.525	34.2	35.8	35.0
	1.701	30.7	33.1	31.9
	1.768	26.5	27.7	27.1
High	1.117	34.4	33.6	34.0
	1.418	36.9	36.3	36.6
	1.719	38.9	38.9	38.9
	2.321	42.5	46.1	44.3
	2.622	44.2	48.9	46.5
	2.923	45.4	48.3	46.9
	3.099	43.6	44.4	44.0
	3.166	39.4	40.0	39.7

Table 6: Mean CFF as a Function of Target Size and Log of Stimulus Intensities Compensated to Talbot-level

Intensity	Log of Compensated Intensity in ft-candles	TN Mean CFF				BM Mean CFF			
		Visual Angle of Target				Visual Angle of Target			
		1°	2°	5°	10°	1°	2°	5°	10°
Low	-0.281	15.1	16.0	16.9	18.5	16.6	17.2	18.5	22.1
	0.020	15.9	17.6	18.5	21.4	15.9	17.9	21.0	26.9
	0.321	19.4	19.1	22.5	25.1	17.5	20.2	25.6	28.8
	0.923	27.8	28.6	31.8	35.4	25.2	28.5	31.2	33.8
	1.224	30.1	31.6	37.6	38.2	27.8	28.9	33.2	38.2
	1.525	31.2	34.2	34.4	37.0	30.2	33.8	36.5	42.6
	1.701	26.4	30.1	31.6	34.8	26.2	29.4	37.0	39.6
	1.768	22.9	25.0	27.6	30.5	20.6	25.1	31.4	33.8
High	1.117	31.4	34.8	35.5	36.1	25.6	30.9	37.8	40.1
	1.418	32.1	37.8	38.2	39.4	30.9	32.2	40.0	42.2
	1.719	36.8	36.8	40.9	41.2	32.5	36.6	42.5	44.1
	2.321	37.8	42.1	45.0	45.1	40.2	44.8	48.4	50.9
	2.622	40.1	44.2	46.4	46.0	44.2	47.4	50.0	53.9
	2.923	44.0	46.1	45.6	46.0	42.0	47.5	52.0	51.6
	3.099	41.0	43.5	43.2	46.5	39.8	42.8	46.8	48.4
	3.166	37.0	38.5	40.0	42.2	35.1	38.4	42.0	44.5

Table 7: Summary Representing the Linear Regression of Mean CFF across the Logarithm of Stimulus Intensities Compensated to Talbot-level

Observer	Visual Angle of Target	Regression Coefficient	Intercept	Correlation Coefficient
TN	1°	0.46	17.0	0.90
	2°	0.50	19.2	0.89
	5°	0.52	23.4	0.87
	10°	0.47	27.6	0.90
BM	1°	0.45	18.5	0.89
	2°	0.49	19.9	0.90
	5°	0.46	22.3	0.91
	10°	0.45	24.5	0.89
Means for TN averaged across Target Size		0.46	21.3	0.89
Means for BM averaged across Target Size		0.48	21.2	0.90
Mean of Data Combined (TN and BM)		0.48	21.6	0.90

FIGURES

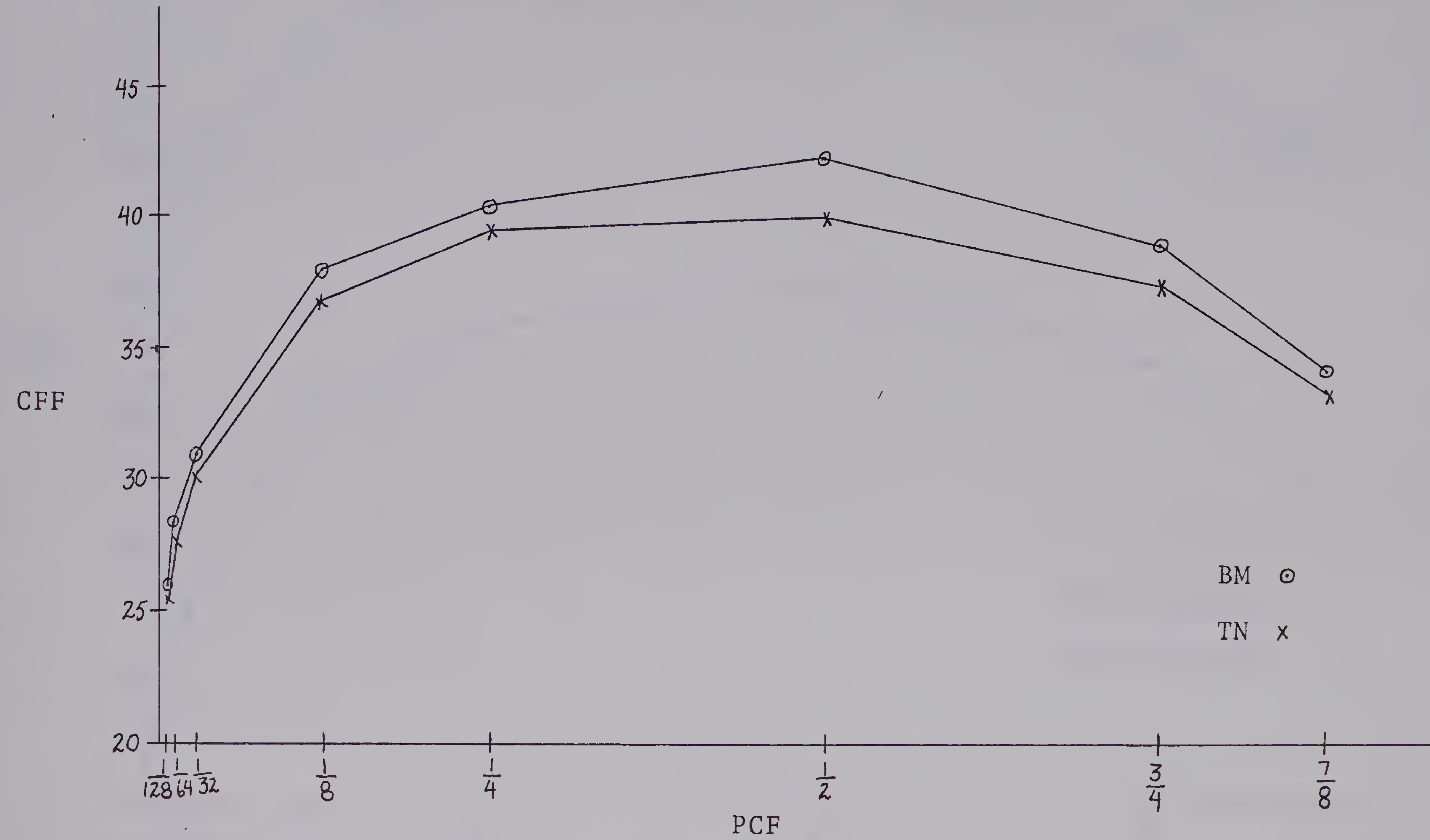

FIGURE 1 Mean CFF as a Function of PCF. Means Plotted For Both Observers.

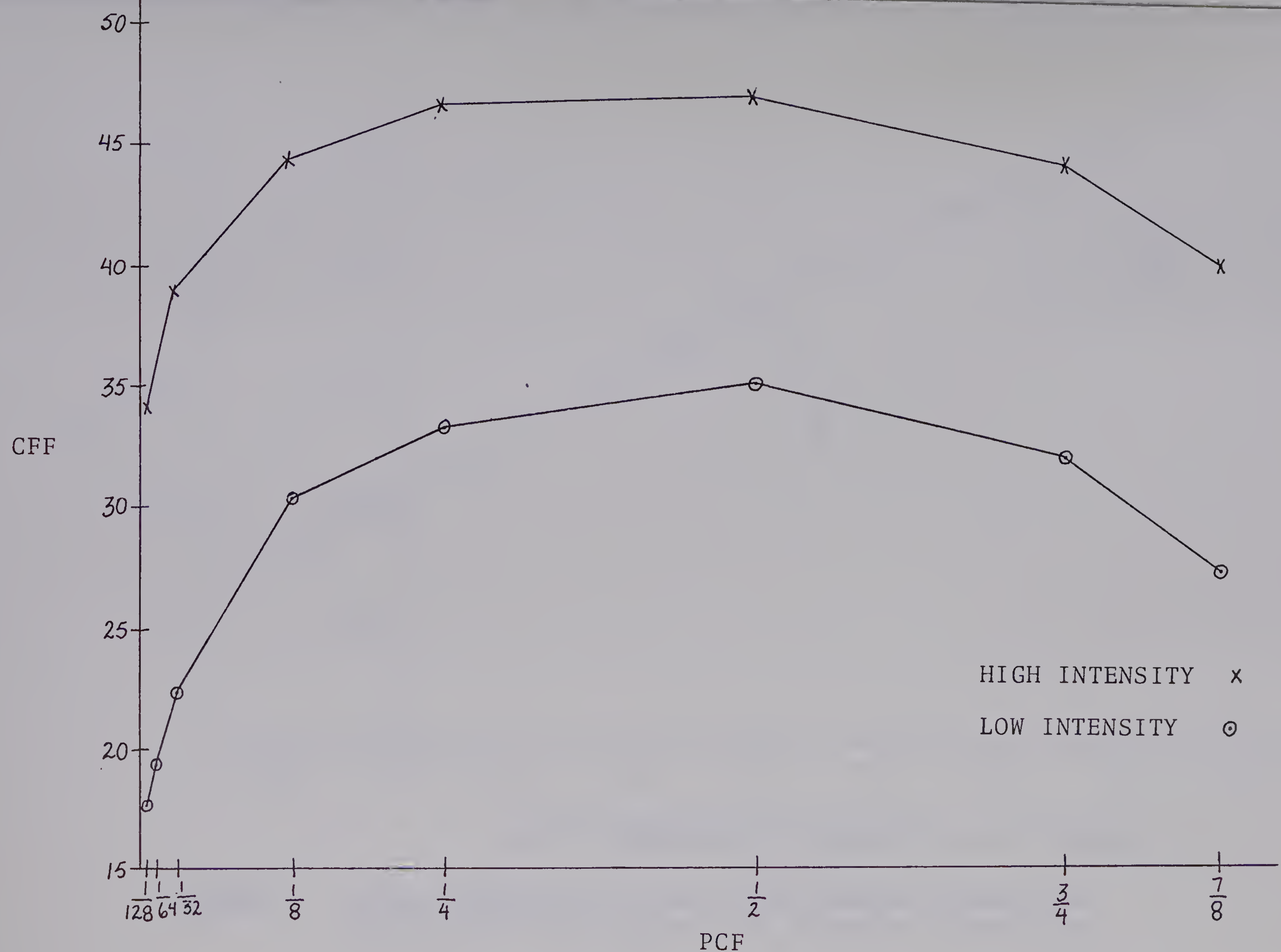

FIGURE 2 Mean CFF as a Function of PCF with Data Plotted for Both High and Low Stimulus Intensities.

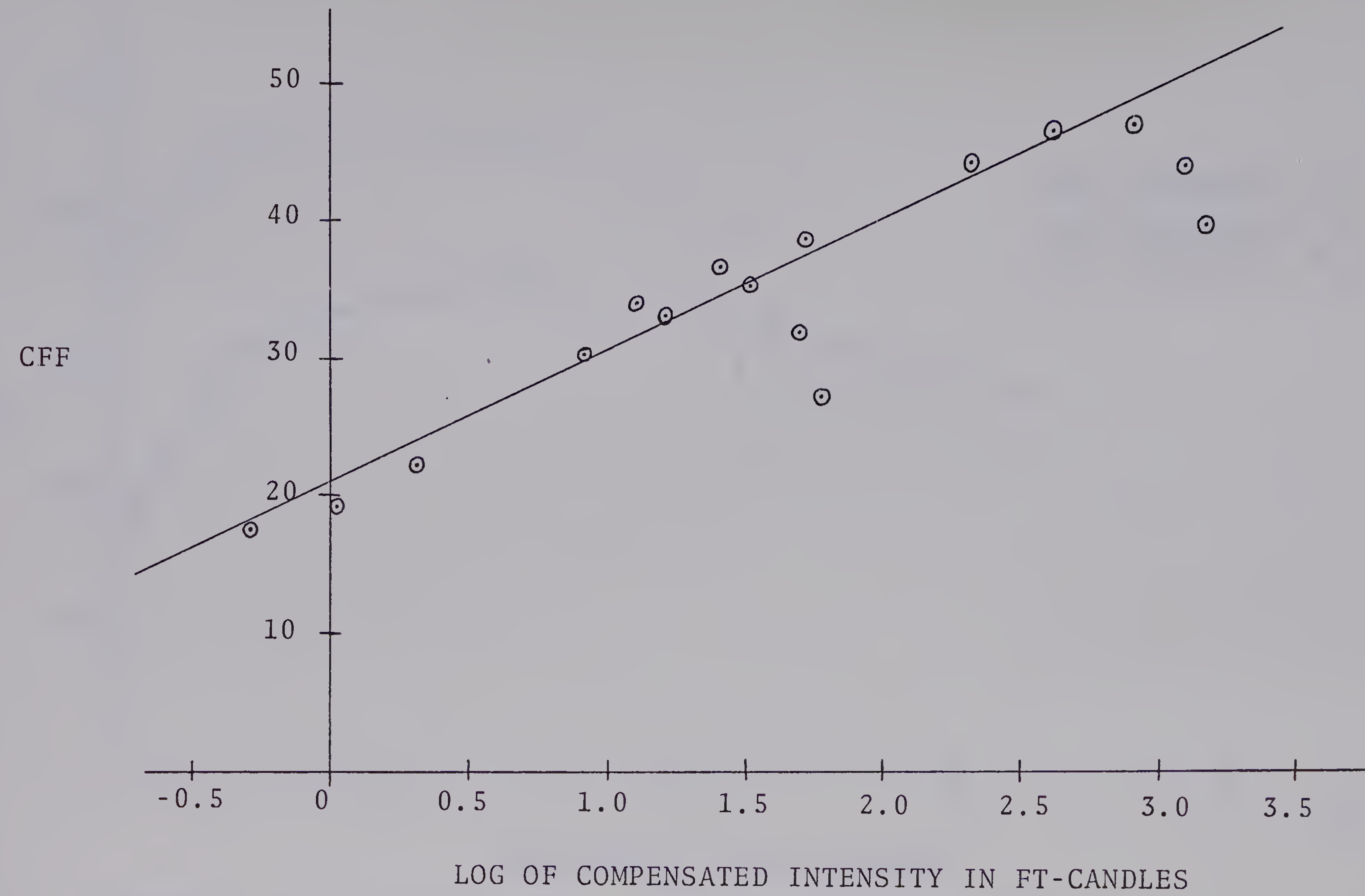

FIGURE 3 Linear Regression of Mean CFF Plotted Across the Logarithm of the Compensated Stimulus Intensities.

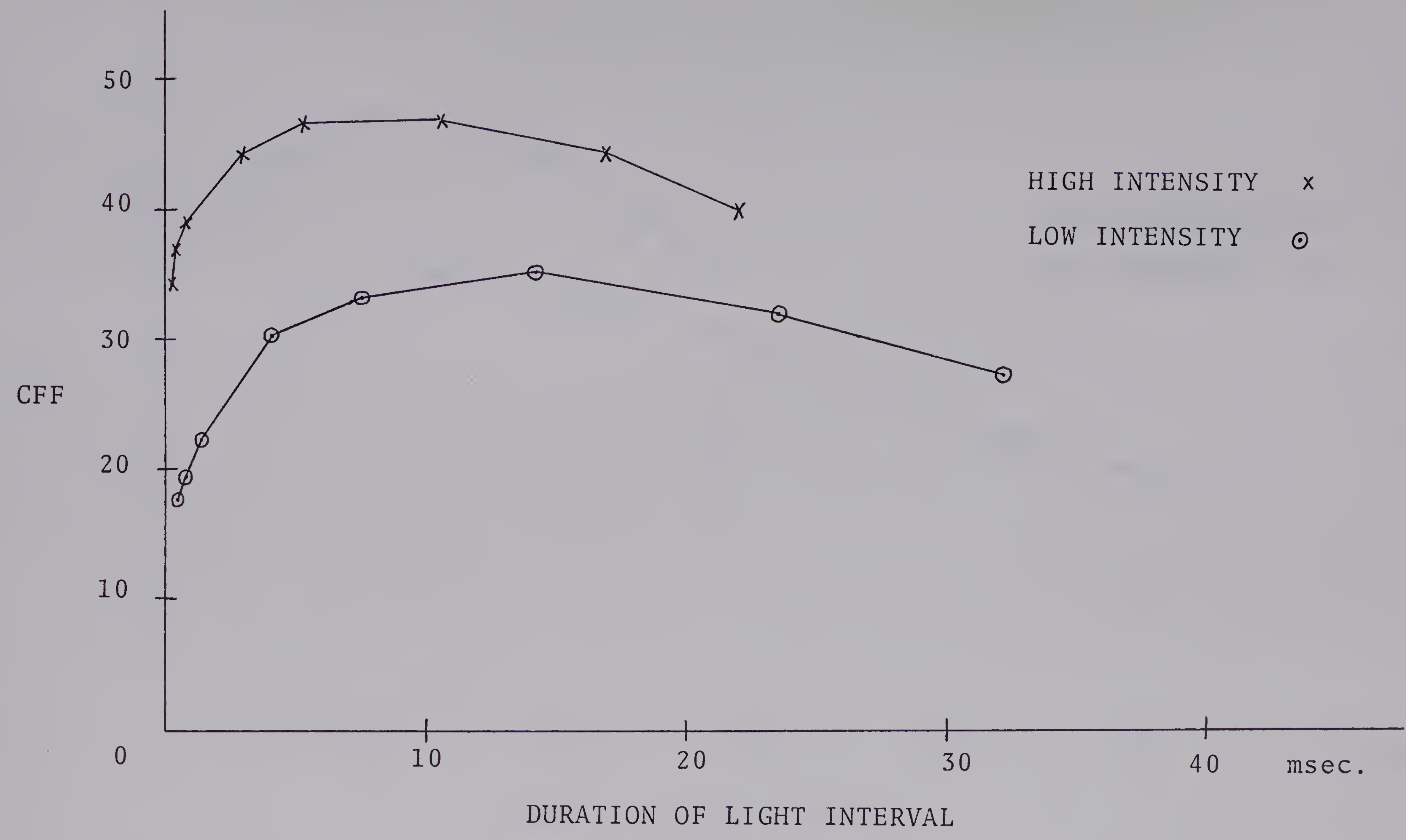

FIGURE 4 Mean CFF as a Function of the Duration of the Light Interval.

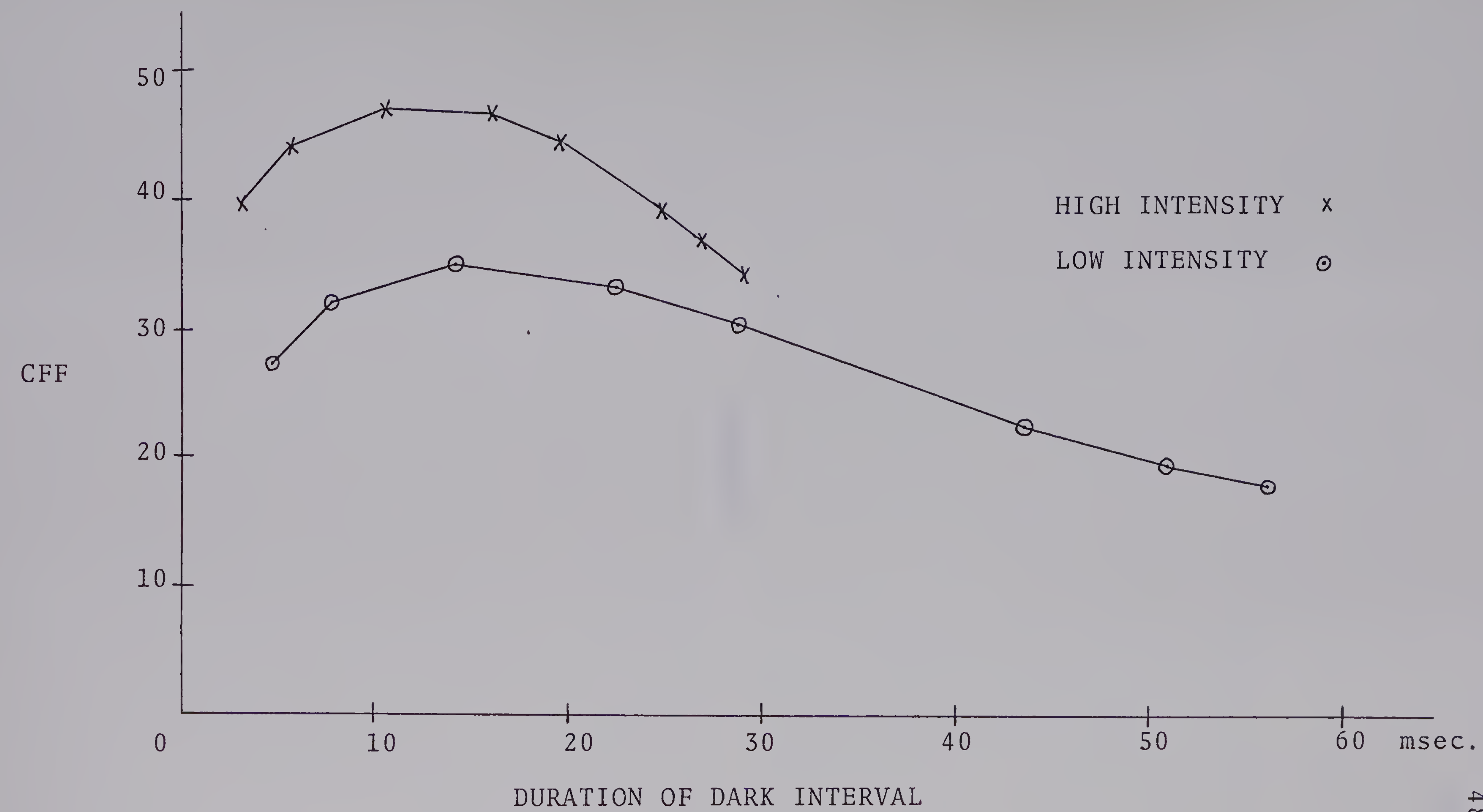

FIGURE 5 Mean CFF as a Function of the Duration of the Dark Interval.

APPENDIX

APPENDIX A

In order to determine the shape of the pulse-forms, the following calculations were made.

The circumference of the disk (32 inches in diameter) was calculated to be 100.48 inches. Since there were six pulses delivered when the disk made one complete revolution, it was calculated that the edge of the episcotister had to travel 16.747 inches to complete one cycle.

Using the average over-all CFF for each PCF, the following values were calculated: cycle time at fusion, the speed that the blade was traveling at fusion, and the rise-time at fusion. The latter two values are presented in Table A-1.

By comparing the rise-times with the pulse durations, one can see what proportion of the pulse duration is constituted by on-set and off-set.

Table A-1: Calculated Rise Times and Pulse Durations for Each PCF at CFF

PCF	Pulse Duration in Milliseconds	Rise Time in Milliseconds
1/128	0.303	0.289
1/64	0.558	0.267
1/32	1.021	0.244
1/8	3.353	0.200
1/4	6.270	0.187
1/2	12.216	0.182
3/4	19.769	0.197
7/8	26.187	0.223